16

THE FACTOR OF MOISTURE IN FROST ACTION

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by

P. F. LOW
&
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Joint
Highway
Research
Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Informational Report

THE FACTOR OF MOISTURE IN FROST ACTION

TO: K. B. Woods, Director January 29, 1959
Joint Highway Research Project

FROM: H. L. Michael, Assistant Director File: 6-10
Joint Highway Research Project

Attached is a report entitled, "The Factor of Moisture in Frost Action." It has been authored by Prof. P. F. Low of the Agronomy Department and Prof. C. W. Lovell, Jr., of the School of Civil Engineering.

It was presented at the Highway Research Board Symposium on "Highway Pavement Design in Frost Areas: Part I, Basic Considerations," at the annual meeting in January, 1959. The paper was not prepared as a project of the Joint Highway Research Project, but is presented to the members of the Board for their information.

Respectfully submitted,

H. L. Michael

H. L. Michael, Secretary

HLM:ac

Attachment

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Informational Report

THE FACTOR OF MOISTURE IN FROST ACTION

by

Prof. P. F. Low, Agronomy Department
and
Prof. C. W. Lovell, Jr., Civil Engineering

Joint Highway Research Project

File: 6-10

Purdue University
Lafayette, Indiana

January 29, 1959

Introduction

The authors have considered their function in preparing this paper to be one of review, summarization and systematizing. An effort has been made to meet the diverse demands of brevity, conciseness and completeness.

Discussion of the role of water in frost action proceeds from basic chemical and physical considerations into those applications of science generally considered basic by the engineer. Initially treated are the structures of water, ice and ionic solutions; followed by the nature of water in clay-water systems, and the forces responsible for its adsorption.

The theory of supercooling is reviewed, as are certain aspects of the freezing behavior of soil water. Data on the quantities, as well as the sources and mechanisms of change in quantity, of moisture experienced under pavements in service are summarized. In conclusion, methods and principles of measuring, predicting and controlling these moisture quantities are outlined.

The Nature of Water, Ice and Ionic Solutions

Studies of the isolated water molecule (e.g., 82)[3] have shown that it consists of a V-shaped arrangement of the atomic nuclei, the H-O-H angle being 105°, and the O-H internuclear distance being 0.97 Å -- Figure 1(a). The dipole moment of the water molecule is 1.83 x 10^{-18} e.s.u., and has been regarded by Bernal and Fowler (11) as being due to the charge distribution

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[3] Numerals refer to items in "References Cited."

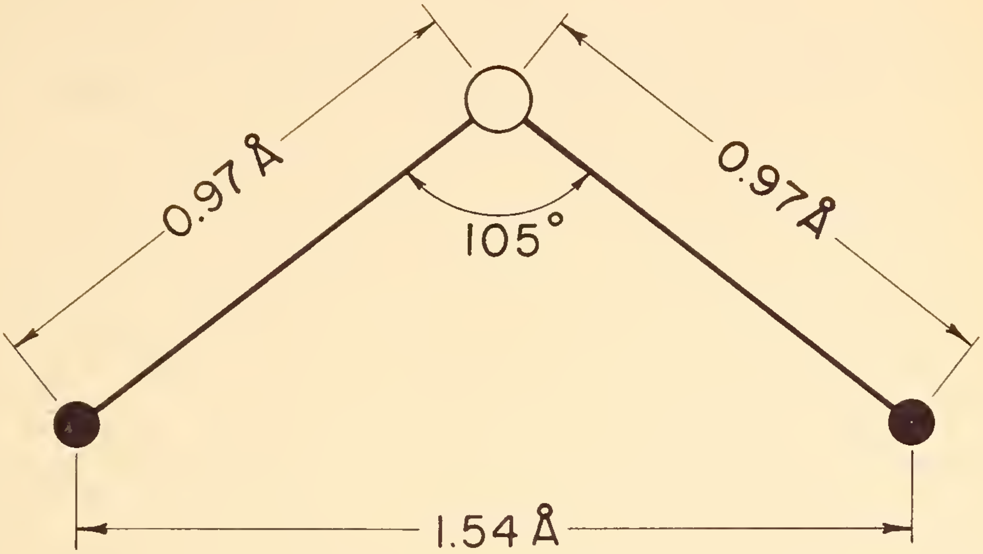


FIG. 1(a)

INTERNUCLEAR DISTANCES AND BOND ANGLE OF THE WATER MOLECULE

(AFTER ROBINSON AND STOKES, 1955)

depicted in Figure 1(b). This geometry and charge distribution give rise to a tendency for water molecules to assume a tetrahedral arrangement as shown in Figure 2. Since the positively charged hydrogen ions of a given water molecule attract the negative charge centers of neighboring water molecules, the molecules are said to be held together by hydrogen bonds.

In ice, the water molecules exist in a tetrahedral arrangement with an O-O distance of 2.76 Å (98, 95). The hydrogen nucleus is not midway between the oxygen nuclei, but is 0.99 Å from one oxygen nucleus and 1.77 Å from the other. Most of the water molecules form the maximum of four hydrogen bonds and, for this reason, ice possesses rigidity. However, ice retains appreciable entropy (i. e., disorganization or randomness), expecially near the melting point (98). Accordingly, it is believed that the molecules can re-orient with considerable freedom, and that the hydrogen ions can re-locate by moving 0.78 Å from a position 0.99 Å from one oxygen to a similar position near the other bonded oxygen. If no hydrogen bonding existed in ice, each water molecule would have twelve nearest neighbors instead of four, and its density would be 1.840 instead of 0.917.

When ice melts, it is estimated that only about fifteen per cent of the hydrogen bonds are broken (98). Therefore, the resulting liquid water retains a loose tetrahedral configuration (11, 65, 98), and is said to have a "broken-down ice structure". There is still a tendency for each water molecule to bond itself tetrahedrally to four neighbors, but the bonds are continually breaking and reforming so that, on the average, each molecule has slightly more than four nearest neighbors, but is bonded to fewer than four of them. As the hydrogen bonds are broken, the resulting fragments tend to pack together as closely as possible, so that some of the water molecules acquire more than four nearest neighbors. This tendency toward

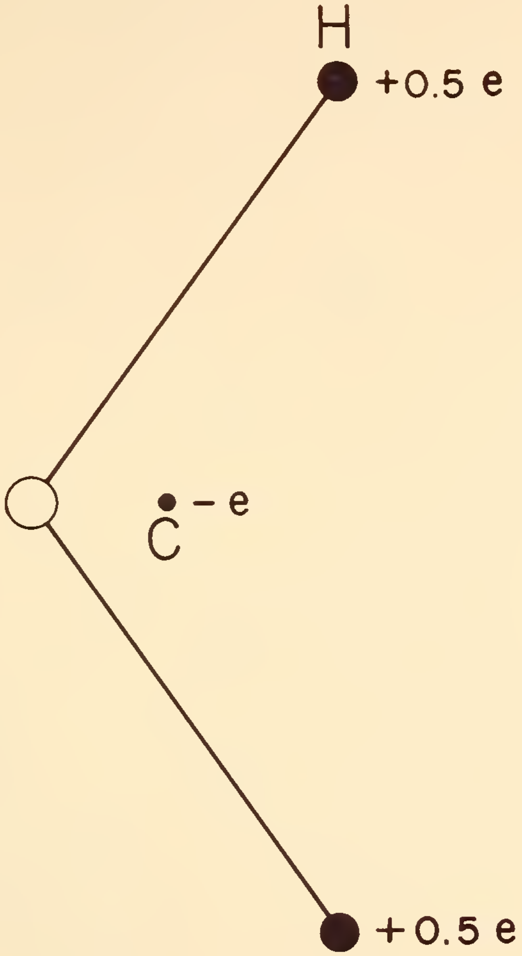


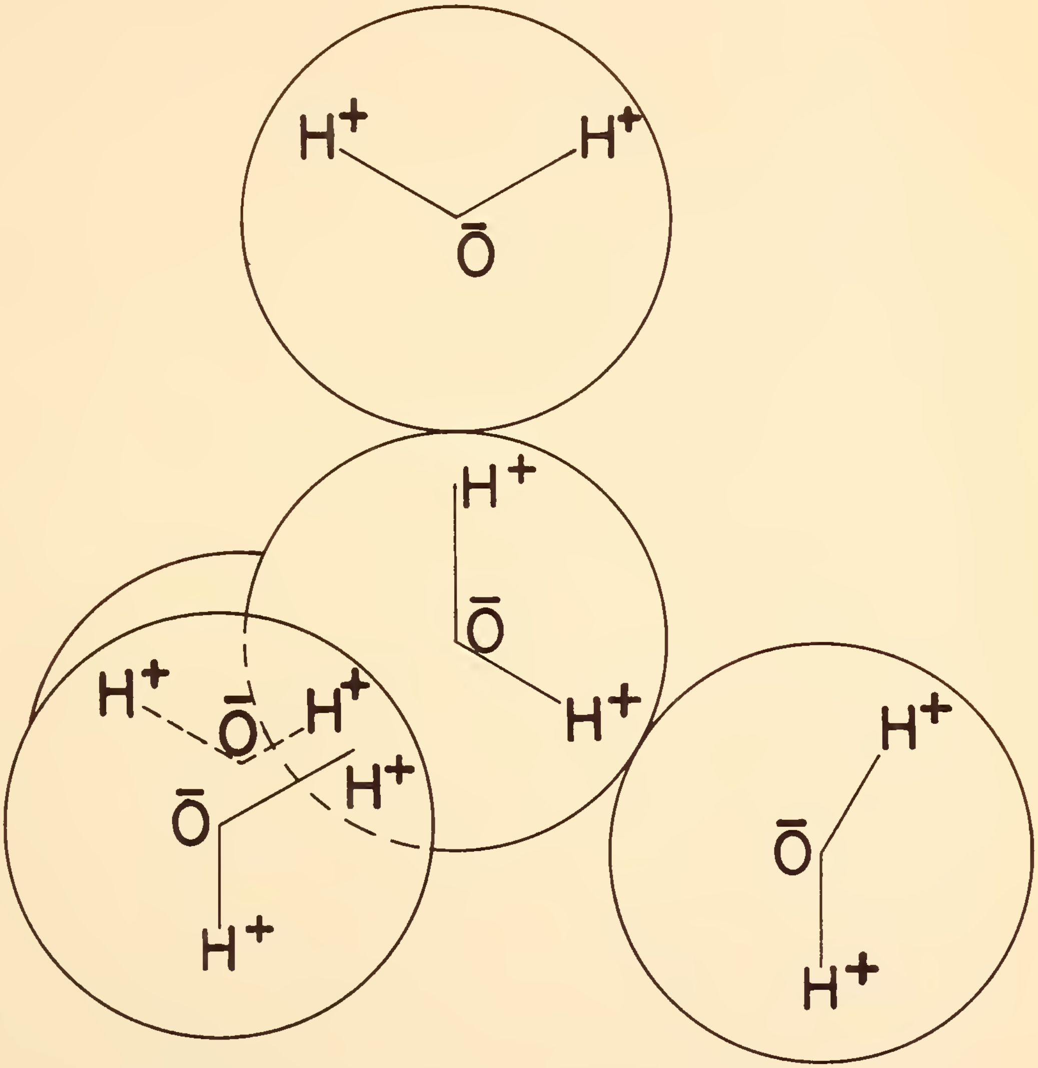
FIG. 1(b)

MODEL OF THE CHARGE DISTRIBUTION IN THE WATER MOLECULE.

C IS TAKEN AS THE CENTER OF THE MOLECULE.

The distance OC is not drawn to scale.

(AFTER ROBINSON AND STOKES, 1955)



TETRAHEDRAL ARRANGEMENT OF WATER MOLECULES

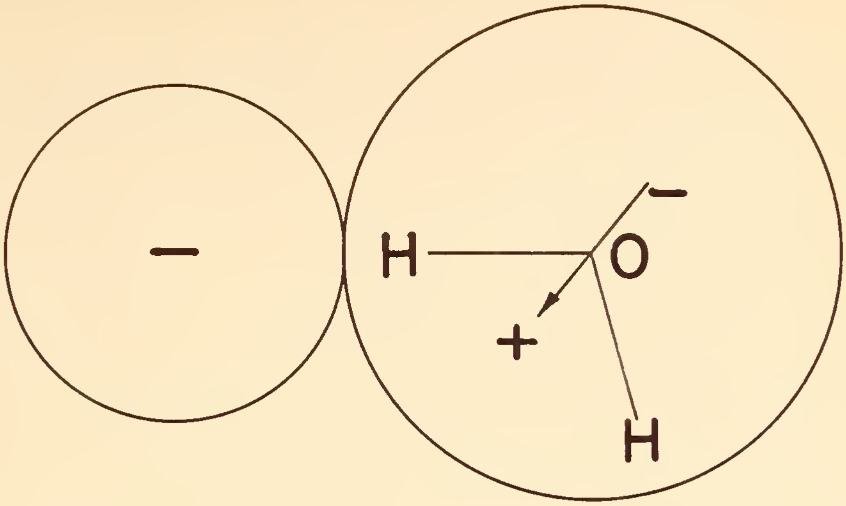
(AFTER BERNAL AND FOWLER, 1933)

FIG. 2

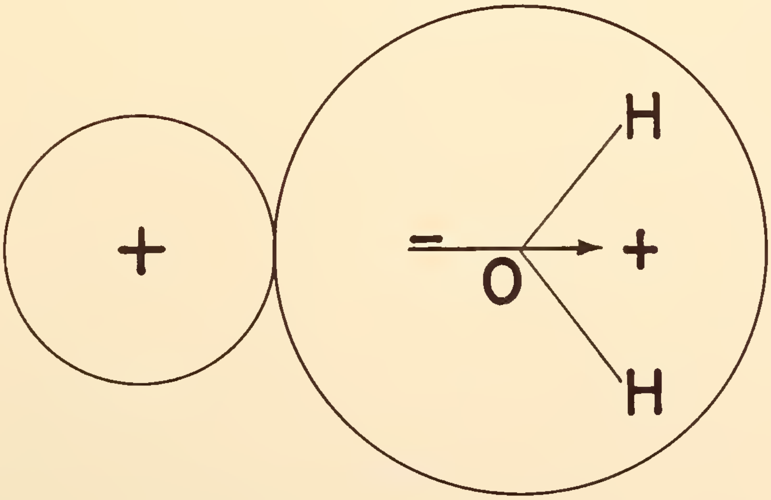
close-packing as bonds are broken explains the volume decrease of about nine per cent on melting, even though the intermolecular distance increases from 2.76 Å to 2.90 Å. As the temperature increases, the increased thermal agitation results in the rupture of additional hydrogen bonds. But the increased agitation also results in an increase in intermolecular distances. The former effect of thermal agitation predominates below 4°C; whereas, the latter effect predominates above 4°C. The result is that water has a maximum density at 4°C. By the time a temperature of 40°C is reached, somewhat more than one-half of the maximum number of hydrogen bonds are still present. Hydrogen bonding exists even at the boiling point. This bonding is responsible for the unusually high values for the melting point, boiling point, dielectric constant, specific heat and viscosity of water.

The solution of electrolytes in water has an effect like that of increasing the temperature, in that the dissolved ions break hydrogen bonds and disrupt the water structure to cause closer packing. It appears, however, that the ions do not appreciably alter the intermolecular distances, because the net effect of electrolyte addition is to increase the density of the water. The disruptive effect of the ions depends on the ionic size, the larger the ion the greater the disruptive effect. These conclusions are based on the X-ray, partial molal volume, and compressibility work of Stewart (117, 118, 119, 120) and of Corey (25); the entropy work of Frank and Robinson (40) and of Frank and Evans (41); the dielectric constant work of Hasted, Ritson and Collie (50); and the viscosity work of Wang (126). The disruptive effect of the ions is probably due to the formation of ion dipole bonds as diagrammed in Figure 3. However, the spacial interference of the ions also plays a part.

For more detailed discussions of water, ice and solutions, the reader is referred to the publications of Bernal and Fowler (11), Llewellyn



ANION HYDRATION



CATION HYDRATION

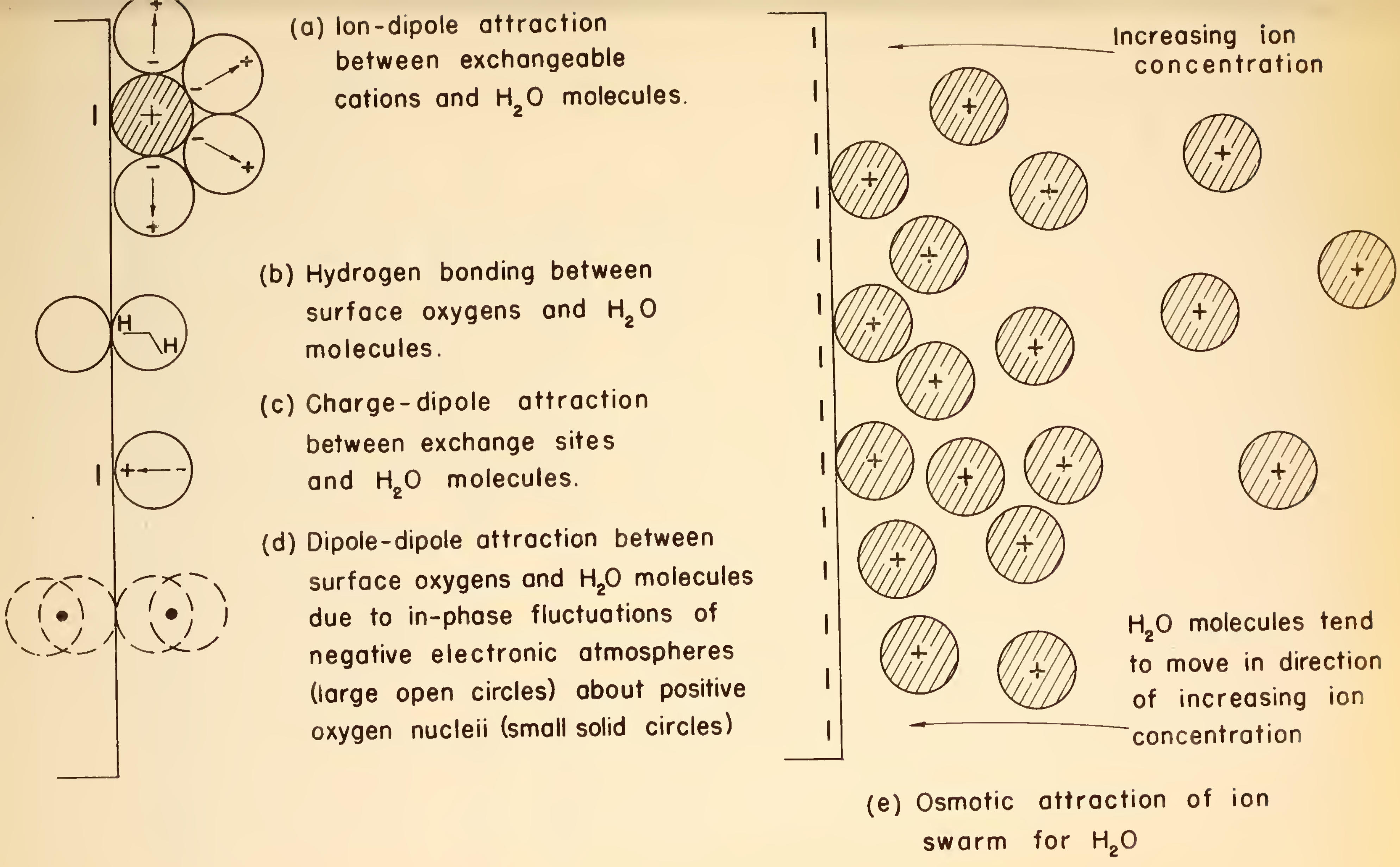
FIG. 3

(72), Pauling (98), Buswell and Rodebush (21), Robinson and Stokes (10) and Owston (95).

The Nature of Water Adsorbed on Soil Minerals

At the present time, all of the forces responsible for water adsorption by soils are not know. However, it is generally agreed that the exchangeable ions are involved. In the earliest stages of water adsorption, these ions form ion-dipole bonds with water molecules [Figure 4 (a)], i.e., they hydrate, and thereby hold water to the mineral surfaces (125, 93, 53, 104, 43, 89, 66, 83). With the addition of morewater, the ions dissociate from these surfaces to form diffuse ion swarms which attract water by osmotic forces (114, 37, 34, 51, 127, 92). Attraction of this kind is depicted in Figure 4 (e).

The mineral surfaces also attract water. This attraction is probably due to hydrogen bonding between the water molecules and oxygen or hydroxyl ions in these surfaces [Figure 4 (b)]. Hendricks and Jefferson (52) and Macey (79) have proposed possible water structures which might result from such bonding. But other kinds of bonding could be involved. For example, the negative charges in the mineral might attract the positive ends of the water dipoles. This attraction could be between individual charges and water dipoles [Figure 4 (c)] or it could be between the electric field produced by the cumulative effect of these charges and the water dipoles. Or the instantaneous fluctuations in charge distribution of the surface atoms could induce in the water molecules similar fluctuations in phase with themselves [Figure 4 (d)]. Regardless of the nature of the bonds the initial layer of water molecules would be strongly oriented. This oriented layer would, in turn, orient the next layer, and so forth. Thus, by relayed action, thick oriented layers of water molecules could be built up.



(a) Ion-dipole attraction between exchangeable cations and H_2O molecules.

(b) Hydrogen bonding between surface oxygens and H_2O molecules.

(c) Charge-dipole attraction between exchange sites and H_2O molecules.

(d) Dipole-dipole attraction between surface oxygens and H_2O molecules due to in-phase fluctuations of negative electronic atmospheres (large open circles) about positive oxygen nuclei (small solid circles)

Increasing ion concentration

H_2O molecules tend to move in direction of increasing ion concentration

(e) Osmotic attraction of ion swarm for H_2O

WAYS IN WHICH WATER MIGHT BE ATTRACTED TO MINERAL SURFACES

An oriented or ordered structure exists in the water adsorbed on at least a few soil minerals. Anderson and Low (4, 77) observed that the density of the water adsorbed on montmorillonite was less than the density of normal water up to distances of the order of 80 Å from the clay surface. The adsorbed water density decreased with proximity to the clay surface, and with a decrease in temperature. Figure 5 shows the data for potassium bentonite. Since exchangeable cations would disrupt this water structure and tend to increase its density, the clay surface must have been responsible for its development. Evidently, the regularity and extent of the adsorbed water structure increases, not only with a decrease in thermal agitation as the temperature is lowered, but also with an increase in cation dissociation from the clay. This fact is indicated by the following observations:

(1) The activation energy for ionic movement, which depends on the coherence of the adsorbed water structure, increases with increased ionic dissocation from the clay(78).

(2) Supercooling of water in clay suspensions, which should be augmented by structural development in this water, increases with increased ionic dissociation from the clay as indicated by zeta potential measurements (33).

(3) Unfrozen water in clay pastes at -5.0°C increases with increased ionic dissociation from the clay, even though the ions are not sufficiently concentrated to prevent freezing at this temperature (51).

(4) Unfrozen water in clay pastes at -5.0°C increases with clay swelling, and is more extensive on external surfaces than on internal surfaces[4] (51).

It can be postulated that structural development in the adsorbed water is enhanced by increased ionic dissociation from the clay, because the disruptive effect of the ions is less when they are distributed through a relatively large volume than when they are concentrated at the surface

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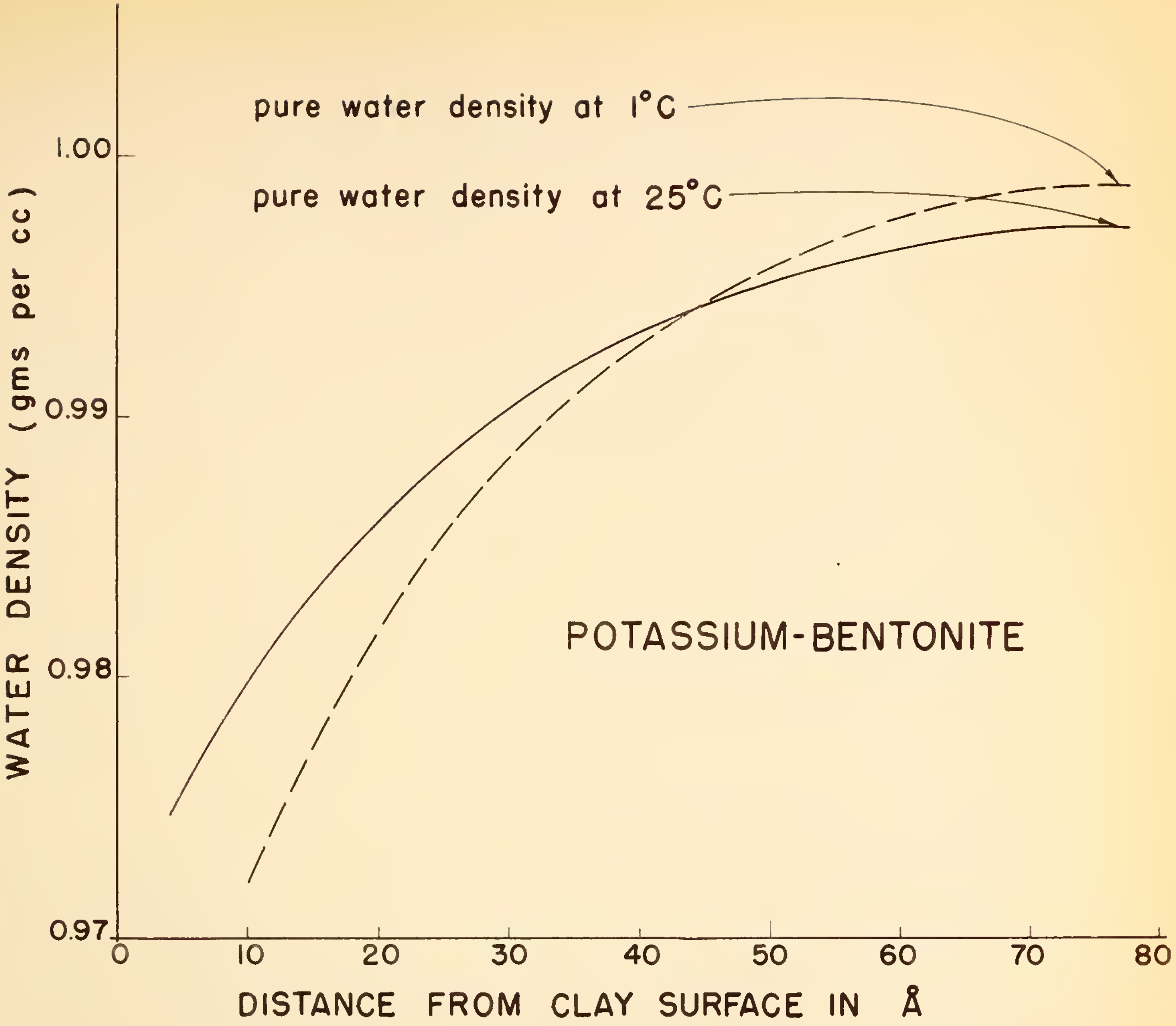
[4] Note that the dissociation of cations from clay surfaces should depend partly on the proximity of adjacent surfaces, the nearer the surfaces, the less the dissociation.



The change in water density with distance from the surface of potassium bentonite at two temperatures (From data by Anderson and Low, 1958)

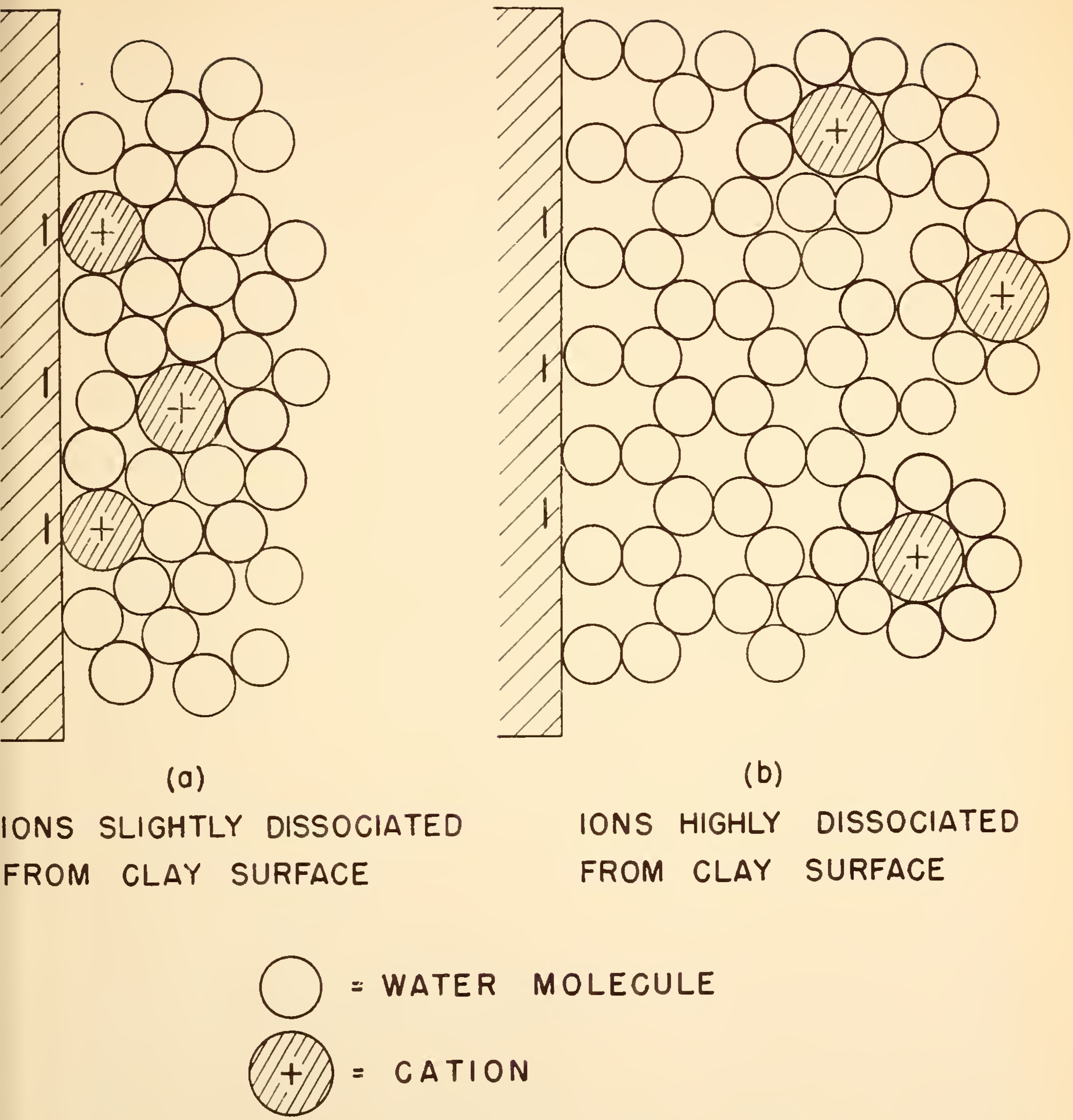
FIG. 5

where the structure is "anchored". Figure 6 illustrates this concept. The structure imparted to the water by the clay surface is not that of ice, because the adsorbed water super-cools extensively; nor is it entirely rigid, because ion exchange occurs readily.

Several investigators (89, 92, 19, 133, 39) have used X-ray diffraction techniques to measure c-axis spacings of clay samples at various degrees of hydration, and have observed that expansion of the lattice layers occurs in definite increments. These increments approximate the diameter of the water molecule, or multiples thereof, up to spacings of 18 Å for montmorillonite. The general conclusion drawn from the results is that successive layers build up on the clay surface as it hydrates. Since it is not yet possible to locate individual water molecules by X-ray measurements on clay-water systems, no conclusions regarding the exact arrangement of the adsorbed water molecules are justified.

Measurements of the dielectric properties of clay-water systems have indicated that the structure of the adsorbed water is different from that of normal water. Muir (91) examined the dielectric properties of hydrated samples of kaolinite, halloysite, metahalloysite and talc at different frequencies and at different degrees of hydration. He found that the frequency of maximum dielectric absorption for the first layer of water was relatively low, and was nearly the same for all the minerals tested. Hence, he concluded that the first layer of water was strongly adsorbed, with about the same intensity regardless of mineral type. As successive layers of water were added, the frequency of maximum absorption increased, suggesting reaction of the less organized outer layers with the first. Palmer, Cunliffe and Hough (96) observed that the dielectric constant of water on mica decreased, with calculated film thickness, from more than 20 for films about five microns thick to less than 10 for films about two microns thick.

FIG. 6



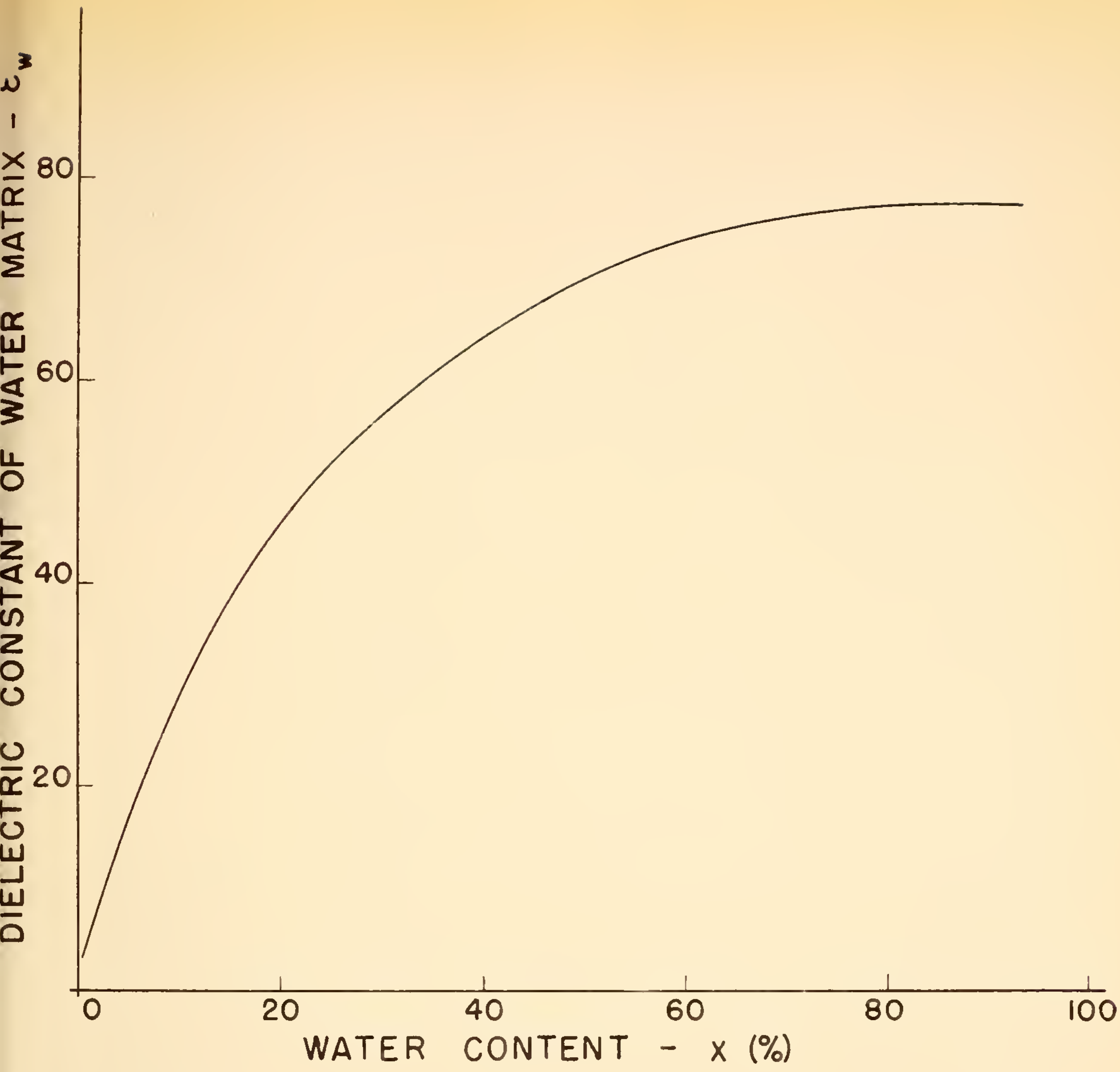
(a) IONS SLIGHTLY DISSOCIATED FROM CLAY SURFACE

(b) IONS HIGHLY DISSOCIATED FROM CLAY SURFACE

The effect of ion dissociation on the Surface-Induced Water Structure. (Illustrative only. Not intended to represent actual molecular arrangement)

They also observed that, as in ice, the dielectric constant of the adsorbed water changed rapidly as the frequency was changed from 2 to 2.5 megacycles per second. Since neither the dielectric properties of free water or mica are frequency sensitive over this range, they concluded that the adsorbed water approached the same degree of crystallinity found in ice. Cownie and Palmer (28) and Palmer (97), using an unspecified wet clay, found that the dielectric constant increased from a value of about three to a value of about fifty in moving from zero moisture to 80 per cent moisture (Figure 7). Thus, the evidence from measurements of the dielectric constant indicates that water is strongly ordered at mineral surfaces, the degree of order decreasing with distance from these surfaces.

If the adsorbed water possesses a structure which is more ordered than that of normal water, its viscosity should be greater than the viscosity of normal water. Very little direct information is available in this regard. However, Macey (79) observed that none of the existing theories on water flow through porous media could be applied to clays without assuming that part of the water was immobile, i.e., that its viscosity was infinitely high. Carman (23) and Von Engelhardt and Tunn (124) were obliged to make the same assumption to explain their data. Macey also found that the conductivity of clays for non-polar liquids was of the order of 10^4 to 10^6 times that for water, suggesting that, despite differences in clay packing, the viscosity of the water was unusually high. The work of Rosenqvist (109) supports these observations. By making certain assumptions relative to the geometry of the pores and using experimental data, Rosenqvist calculated a diffusion coefficient for deuterium oxide in the pores of a clay paste which was only about five per cent that of pure water. Recently, Low (78) has shown that the activation energy for ion movement in the adsorbed water is



Variation of the dielectric constant of water in a wet clay with the water content (After Palmer, 1952)

FIG. 7

higher than the activation energy for ion movement in pure water. The available evidence indicates that clay-adsorbed water has an unusually high viscosity. But it should be noted that electroviscous effects (36) or counterelectro-osmotic effects (87) might account for part of the retardation of water flow in porous media. It is unlikely that they account for all of it (54). A hypothetical viscosity vs. distance curve is shown in Figure 6.

The thermodynamic properties of water adsorbed on soil minerals are also different than those of normal water. For the equation,

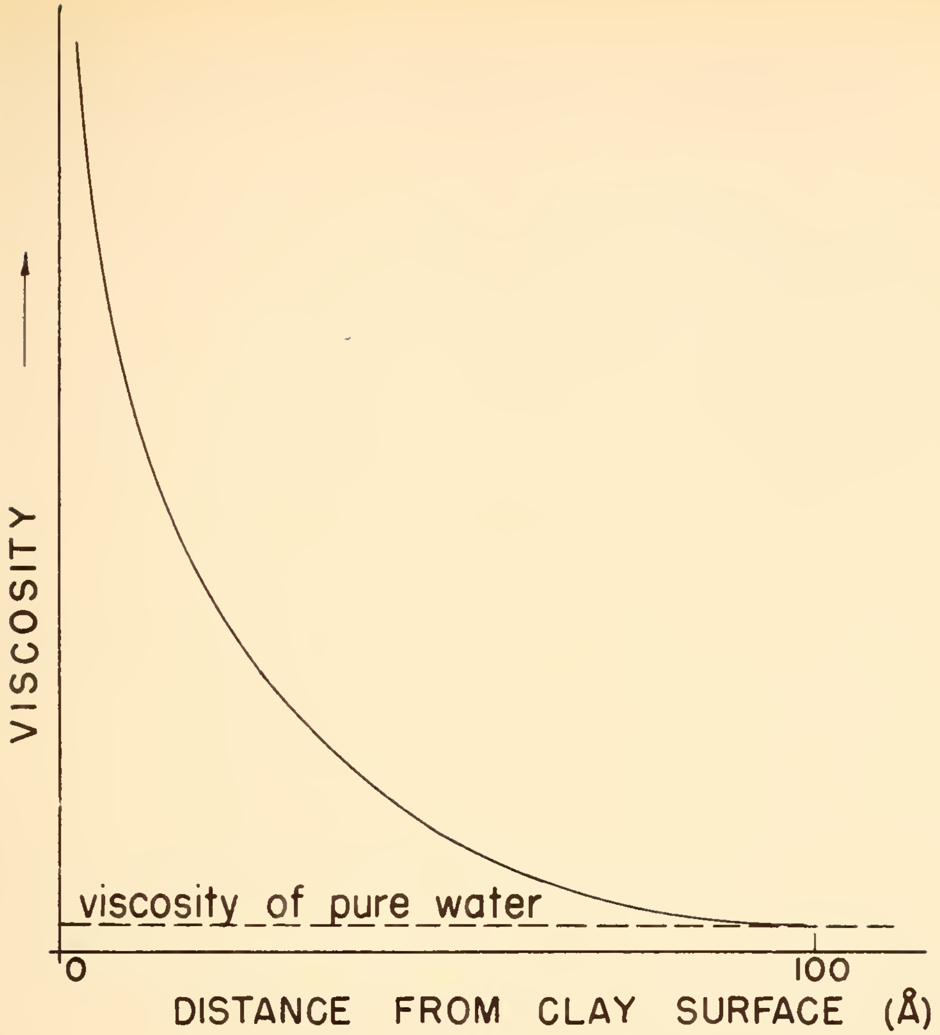
$$\overline{F} - \overline{F}^{\circ} = -\overline{V}\pi$$

where $\overline{F}$ and $\overline{F}^{\circ}$ are the partial molar free energy of the soil water and pure water, respectively, $\overline{V}$ is the partial molar volume of the soil water and π is the swelling pressure, we see that the partial molar free energy of the soil water is less than that of pure water as long as the soil swells in pure water. Clay soils will swell in pure water until films as thick as 200 Å have developed on the particle surfaces (114, 37, 14, 51, 120, 92).

The heat content of this water is also less than that of normal water. There is considerable evidence (19, 113, 109, 116, 88, 47) which shows that heat is lost on the adsorption of water by clays until water films of appreciable thickness are formed. And the initially adsorbed water has a heat content less than that of ice (109).

The data on the entropy of soil water are limited. However, they show that the soil water has a higher degree of order than normal water, up to water contents as high as the field capacity (106, 6). The water in the first monolayer on kaolinite is more ordered than ice (45).

For additional information on the nature of adsorbed water, the reader is referred to the discussions of Grim (47), Williamson (128) and Mackenzie (80).



Hypothetical decrease of water viscosity with distance from the clay surface.

FIG. 8

The Supercooling and Freezing of Adsorbed Water

The evidence presented in the previous section shows that the structure and properties of water are altered when adsorbed on soil minerals. Now let us examine the consequences of this alteration on the supercooling and freezing of the water. The discussion will be brief because the subject of freezing will be treated in greater detail elsewhere in this Symposium.

According to the nucleation theory of Turnbull and Fisher (122), as applied to water by Mason (85, 86),

$$\log J = 32.84 + \log T - \frac{U}{2.303kT} - \frac{760\ \sigma^3}{(To-T)^2T}$$

where J is the rate of production of ice nuclei of critical size, T is the absolute temperature, U is the activation energy for the diffusion of water molecules across the water-ice interface, σ is the interfacial energy between water and ice, and To is the thermodynamic freezing point. A nucleus of critical size is one which is just large enough to grow to an ice crystal rather than evanesce. Now U is related to the viscosity η by the expression (5, 44),

$$\eta = Ae^{\frac{U}{kT}}$$

where A is a constant; hence the rate of production of ice nuclei of critical size is expected to be small, i.e., we can expect a tendency for the water to supercool if the viscosity of the water is high and if the interfacial tension against ice is large. There is evidence that the viscosity of the adsorbed water is unusually high. In addition, evidence

exists that the adsorbed water has a different structure than normal water, and, for this reason, should have a different interfacial tension against ice. If we assume that this interfacial tension is increased by the clay induced modification in the water structure, the observed supercooling of water in clays and soils can be explained.

The freezing point of water can be lowered by increasing the ion concentration and pressure (10, 39) and by lowering the potential energy of the water relative to that of ice (6). Undoubtedly, the ion concentration and hydrostatic pressure are greater in the region of the charged mineral surfaces than in the bulk of the soil solution. Also, if an attracting force exists between the water and mineral surfaces as indicated, the potential energy of the water should be lower in this region. It is not surprising, therefore, that all the water in a clay or soil system does not freeze at the same temperature; the adsorbed water can freeze only at a lower temperature (51, 15, 3, 20, 76).

In view of the ion concentrations and probable hydrostatic pressures in the systems studied thus far, it appears that these factors alone cannot account for the observed amounts of water remaining unfrozen. Consequently, the reduction in the potential energy of water near the mineral surfaces must also be a factor. This factor has not been generally recognized.

The Quantity of Moisture Under Pavements

Prediction of the moisture content or degree of saturation to be expected beneath a pavement at a given time is in general a complicated matter. The multitude of variables and uncertain boundary conditions have limited the scope and conclusiveness of both the field measurements and rational or calculation type of approach.

In this regard, consider first the variable of control of compaction moisture content, which is influenced by the soil texture, the type and magnitude of compactive effort, and the efforts of the engineer to specify and control it. As a result of a number of recent studies, it is anticipated that progressively less emphasis will be placed on the simple achievement of high densities, and more on the specification of compacted moisture-density conditions capable of producing desired, predetermined properties in the service subgrade or embankment.

For example, Foster ([illegible]) and Turnbull and Foster (127) have shown that the strength of a compacted silty material can decrease with increase in density, unless the compaction moisture content is properly controlled. Wilson (129) demonstrated that for cohesive soils the properties of strength, resistance to deformation, permeability, and compressibility can be greatly influenced by variation of only the molding water content. Discussions of these papers point out the manner in which high densities and low molding water contents serve to increase swelling of clays.

Lambe ([illegible]a, [illegible]) has taken a fundamental approach to the matter of compaction moisture content, suggesting that the difference in soil properties wet and dry of optimum is logical in view of the difference in soil particle orientation for the two conditions. Seed ([illegible]), in as yet unpublished research, has successfully applied the flocculent vs. dispersed structure concept in interpretation of laboratory data on compacted clays.

The observations of Hveem and Vallerga ([illegible]) -- with discussion, lend additional support to the belief that compaction specification must become increasing definitive of desired service [illegible]

perties. The trend to better control compaction moisture contents should, as a by-product, aid efforts in measurement and prediction of service moisture conditions.

Prominent among the studies of actual moisture conditions under pavements are those by Kersten (68, 69), Hicks (55), Corps of Engineers (26, 27), Redus and Foster (102) and Redus (103) This listing can be supplemented rather extensively if one includes work where, (a) the data reported are more limited, (b) the moisture measurements are much subordinated to another investigational endpoint, and (c) the observations are made under other than a pavement cover. The data reported serve to emphasize the relative importance of such factors as: type of pavement (including base and sub-base layers); loading and its capacity to produce densification; age and condition of the pavement; texture and initial condition of subgrade or embankment; the environment--topographic position, ground water level, climate, season, severity of frost action; and depth, position and frequency of sampling.

These investigations show: (a) that the more clayey soils achieve higher degrees of saturation in service than do soils of low plasticity; (b) that climate, and more particularly precipitation, has the anticipated effect at shallow depths; (c) that the moisture quantities show continuous, if small, variation with the seasons, but with an increase trend to some critical age; and (d) that moisture gradients exist laterally with respect to the pavement, as well as with depth under the pavement. Beyond this area of general agreement in data are important differences, assumed to be peculiar to the study sites, and perhaps also to the investigational perspectives.

A generalized concept of the sources of sub-pavement moisture is presented in Figure 9.

(1) Moisture may permeate from the above, [illegible] coarse grained layers are present, or where surface drainage facilities in the immediate vicinity are inadequate. (2) The water table may rise, and indeed may be depended upon to do so in the winter and [illegible]. (3) Surface water may enter joints and/or cracks in the surfacing, enter at the edges of the surfacing, or percolate through the [illegible] and shoulders. (4) Water may move laterally or (5) vertically in capillaries or interconnected water films. (6) Moisture may move in vapor form, depending upon the existence of adequate gradients and air void space. Moisture can be removed from the soil by reversing the above [illegible] and substituting evaporation for (3).

The study of mechanisms by which moisture moves in a porous medium is basic to a number of scientific and engineering disciplines. Certain quantities are "free" to move by gravity flow; other moisture is "held", and can move only in response to more complex energy gradients. [illegible] differences are capable of producing considerable liquid flow when the soil is saturated or nearly so. Temperature gradients provide prime motivation for vapor movement, particularly when soil texture and water table position combine to produce a relatively low degree of saturation.

The topic of moisture migration has been extensively studied with a primary reference to highway problems — Russell and Spangler (111), Winterkorn (131), Maclean and Gwatkin (81), Croney and Coleman (27), Road Research Laboratory (105), Wolverton (132), Collins et al (108), Johnson (61); as well as the papers of the "International Symposium on Moisture Conduction in Soils and Similar Systems" (1957-1958) in two parts, one to be published by the Highway Research Board.

The great capacity of the soil freezing process to "pull" moisture into the freezing zone has long been recognized, and reported for both laboratory and field studies — Taber (122), Beskow (12), [illegible] (115), [illegible] (74), Haley and Kaplar (48), and Lovell and Herrin (75). Within the last few years intensive investigations of the details of these moisture motive potentials have appeared in the engineering literature. [illegible]

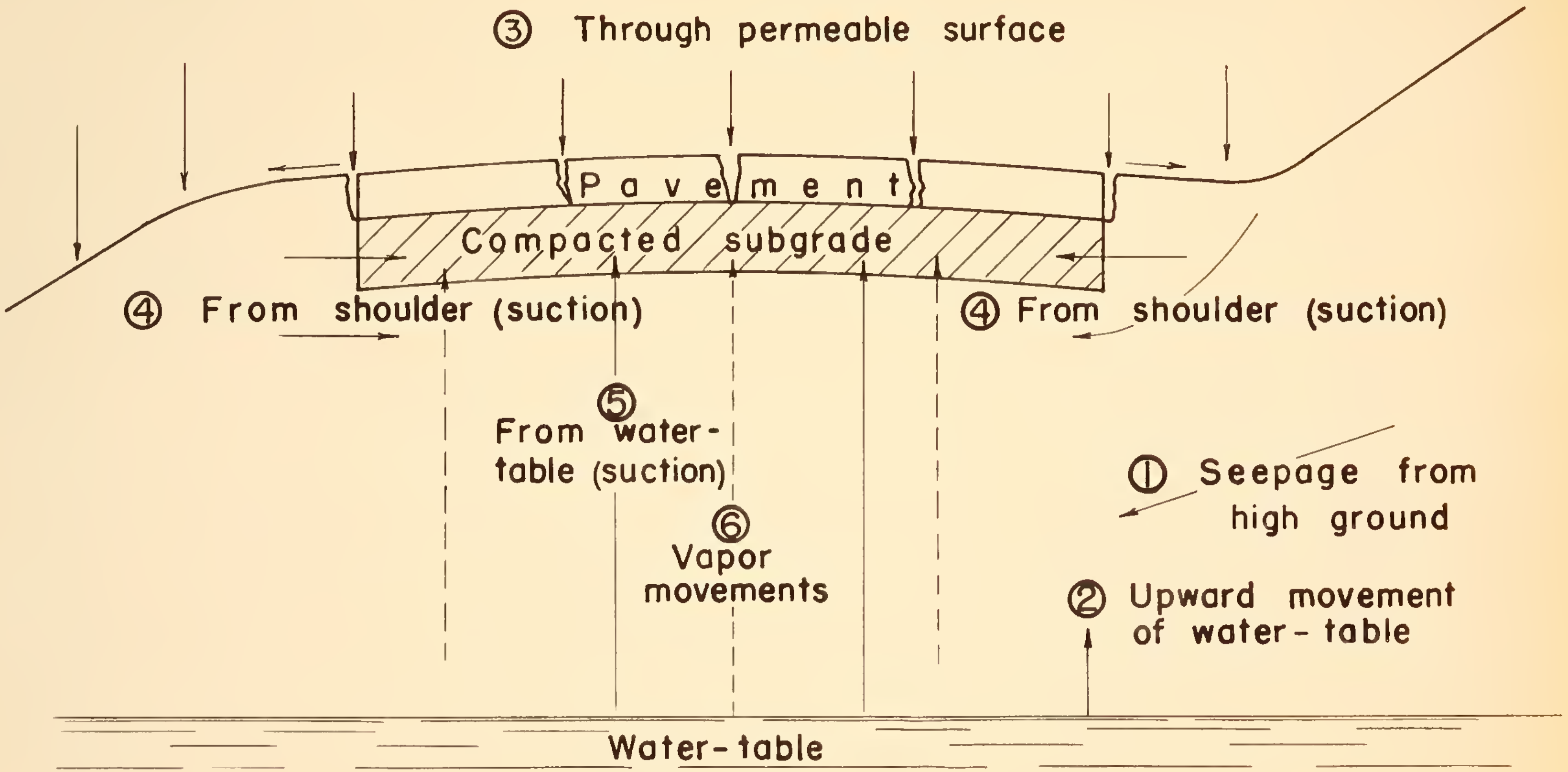

③ Through permeable surface
P a v e m e n t
Compacted subgrade
④ From shoulder (suction)
④ From shoulder (suction)
⑤ From water-table (suction)
⑥ Vapor movements
① Seepage from high ground
② Upward movement of water-table
Water-table

FIG. 9 WAYS IN WHICH MOISTURE CAN ENTER ROAD SUBGRADES

(AFTER ROAD RESEARCH LABORATORY, 1952)

(100, 101), Gold (46), Jumikis (62, 63, 64), and Martin (84). It is found that very considerable suctions are operative for liquid flow to the area of crystallization.

The Determination of Quantity of Moisture

The primary approach to determination of moisture quantities has been experimental, i.e., measurement of in-service conditions. The oldest, and still dominant, measuring technique is the gravimetric method of sampling and oven drying. This technique has very pronounced and obvious deficiencies when applied to the problem at hand.

A variety of techniques of "in-place" moisture measurement have been subjected to experimental or to practical use. Perhaps the best known of these are the electrical resistance cells of Bouyoucos and Mick (16), Bouyoucos (17, 18), and Colman (24). The porous material of these units (plaster of paris, nylon or fiberglas) tends to remain in moisture equilibrium with the surrounding soil. The electrical resistance of the "block" changes with its quantity of moisture, and upon calibration becomes a measure of the moisture in the soil.

Another method, and one of considerable promise, is the neutron method of counting hydrogen nuclei -- Belcher et al (7), Belcher (8), Carlton (22), Horonjeff and Goldberg (57), Horonjeff and Javete (58), and Roy and Winterkorn (112)[4]. In this method, neutrons are emitted, scattered, lose energy and become "slow" after collision with the hydrogen atoms in the soil-water system. As the quantity of moisture (in any form -- solid, liquid or vapor) increases, the count of slowed neutrons increases. Upon calibration, the count becomes a measure of the average moisture content over a

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[4] Contains a very extensive bibliography.

to have strong practical limitations by Aldous and [illegible] (2), and the evaluation of moisture content by measurement of dielectric constant or capacitance — DePlater (34), Downie and Palmer (28), and Palmer (97). The latter technique should be viewed as very much in the experimental stage. In addition, a recent modification of the electrical resistance method utilizes an ionic moisture barrier to filter salts from the moisture being measured. Engineering development of this device has had [illegible] reference to the moisture in hardened concrete — Blythe (13) and [illegible] (70).

A summary view of moisture measurement methods may be obtained by review of Fenner et al (93), Lull and Reinhart ([illegible]) and the references of the Highway Research Board Bibliography ([illegible]). [illegible] and use of all [illegible] [illegible] [illegible] moisture sensitivity, the need for lengthy [illegible] [illegible] [illegible] [illegible] [illegible] others.

An interesting supplementary capacity of the electrical resistance method is that of determination of time or duration of soil freezing — Rowland et al ([illegible]) and unpublished work at the [illegible] Illinois.

The approach of prediction through calculation for equilibrium or maximum moisture contents has been spearheaded by English investigators using the suction concept — Croney et al (30), Croney ([illegible]), and summarized by Croney et al (32). With reasonable limitation on the boundary

conditions, calculated moisture values have been found to check field moisture conditions rather well. Woolorton (132) has recommended as prediction alternates the use of density-moisture change curves or the field moisture equivalent.

The Control of Moisture Quantities

Reference is again made to Figure 7, and to the previous discussion of sources and mechanisms for moisture increase of subgrades and embankments.

Drainage is an obvious method of control for the gravitational water. Much of the water in the pores of the coarse-grained soils is in this category, and it is commonly possible to greatly reduce the degree of saturation of such soils by conventional subdrainage. For example, lateral seepage in granular layers can be intercepted, open graded bases and subbases can be drained, and free water perched in a sandy stratum by a relatively thin layer of low permeability can usually be disposed of by subdrainage. The water table can be lowered by subdrainage in fine grained materials also, but as the soil becomes more clayey, the time required to achieve significant lowering becomes progressively more impractical, and the reduction in degree of saturation effected by the removal of gravitational water becomes rather insignificant.

A number of investigators have addressed the problem of definition of a limiting initial moisture content or degree of saturation, below which ice segregation and frost damage are unlikely. These include Taber (121), Winn and Rutledge (130), Corps of Engineers (26), and Haley (49). This critical quantity of moisture varies with a number of factors, such as the availability of additional moisture and the rate of freezing.

Field observations have revealed that even though the water table often cannot be lowered sufficiently to eliminate frost damage, this damage can be very significantly reduced by lowering of the order of several feet --Beskow (12), Keene (67), Road Research Laboratory (105), and Lawson (71). Experience also favors, as an alternate or supplement to ground water lowering, the use of an elevated grade line.

Certain profile situations need particular drainage attention, due to their tendency to "trap" free water, e.g., Aaron (1). The same is often true of situations where rock underlies the pavement at shallow depth--Bennett (10), Otis (94), and Fuller (42). Drains must of course be open and able to function during the critical thawing period.

Finally, it seems pertinent to mention the use of "barriers" to reduce capillary or vapor movement. The idea of interposing a granular layer which "cuts off" capillary flow is an old one--Beskow (12). Membranes capable of also sharply reducing vapor transmission have received increased recent attention. Particularly interesting, although beset with sizable practical difficulties, is the use of plastic films--Bell and Yoder (9).

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